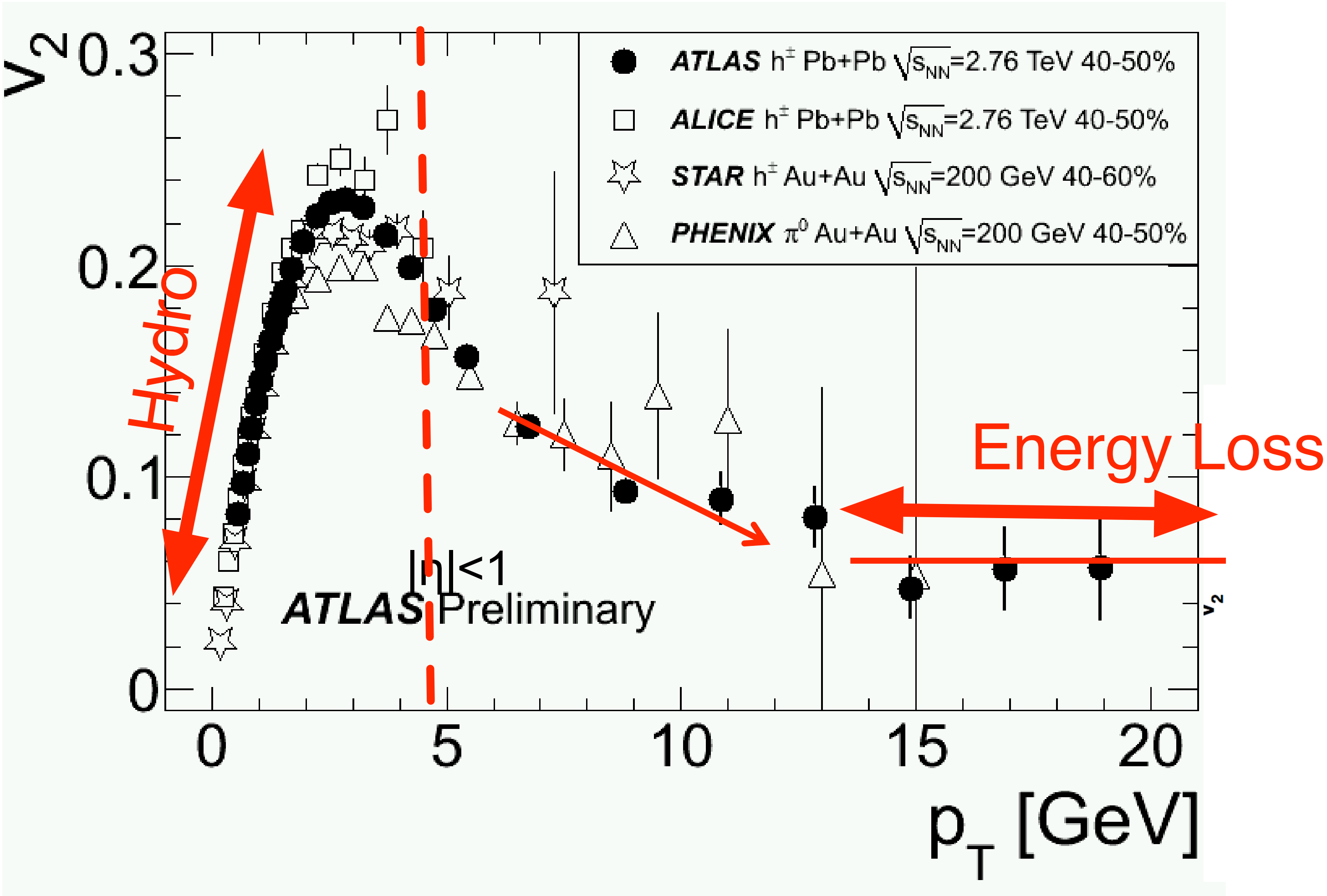
Theoretical Overview – AGS Users Meeting

Derek Teaney

SUNY Stonybrook and RBRC Fellow

Outline

Hydro and Energy loss:



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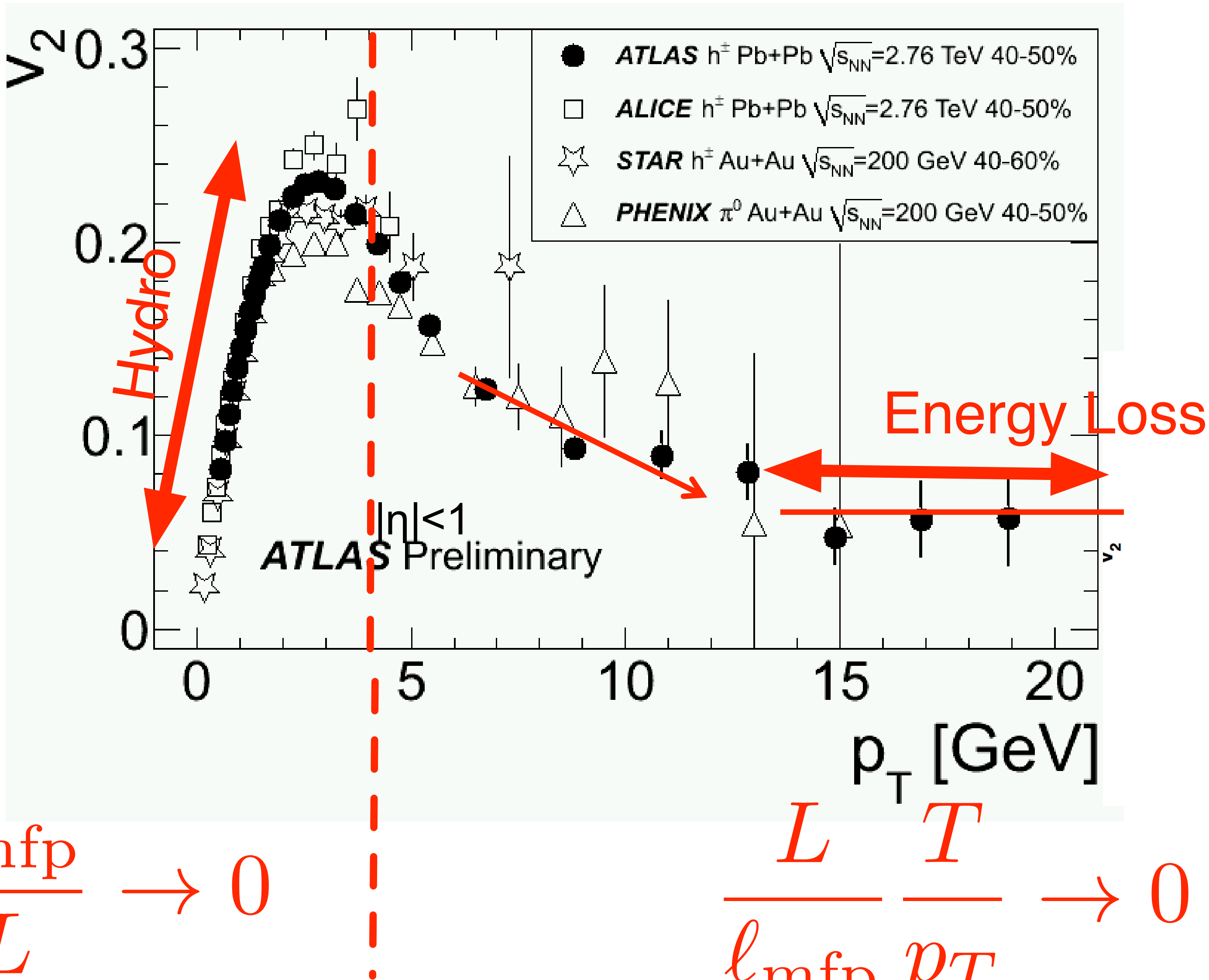


$$\frac{\ell_{\rm mfp}}{L} \to 0 \qquad\qquad \frac{L}{\ell_{\rm mfp}}\frac{T}{p_T} \to 0$$

Hydro

Why I believe that there's hydro at RHIC (and why you should too):

1. ✓ Ideal hydro works kind-of (not for today)

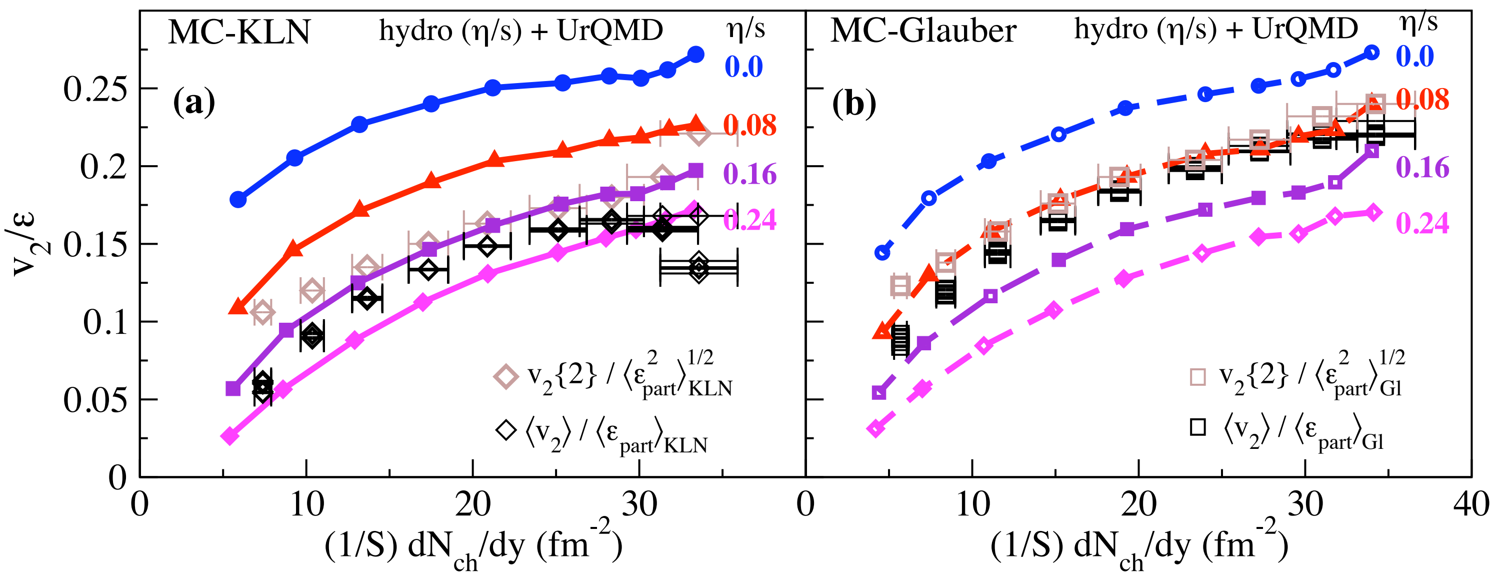
2. Viscous corrections systematically capture deviations of data from ideal hydro

Viscous Hydro – Dependence on System Size

$$T^{\mu\nu} = \underbrace{eu^\mu u^\nu + pg^{\mu\nu}}_{\text{Ideal}} - \underbrace{\eta \langle \nabla^\mu u^\mu \rangle}_{\text{Viscous} \sim \ell_{\rm mfp}/L} + \underbrace{\ldots}_{\text{2nd Order} \sim (\ell_{\rm mfp}/L)^2}$$

- Totally integrated v_2 versus systemsize (centrality) must come out right:
  - Depends on almost nothing except $T^{\mu\nu}$ (e.g. freezeout, $\delta f, \ldots$)

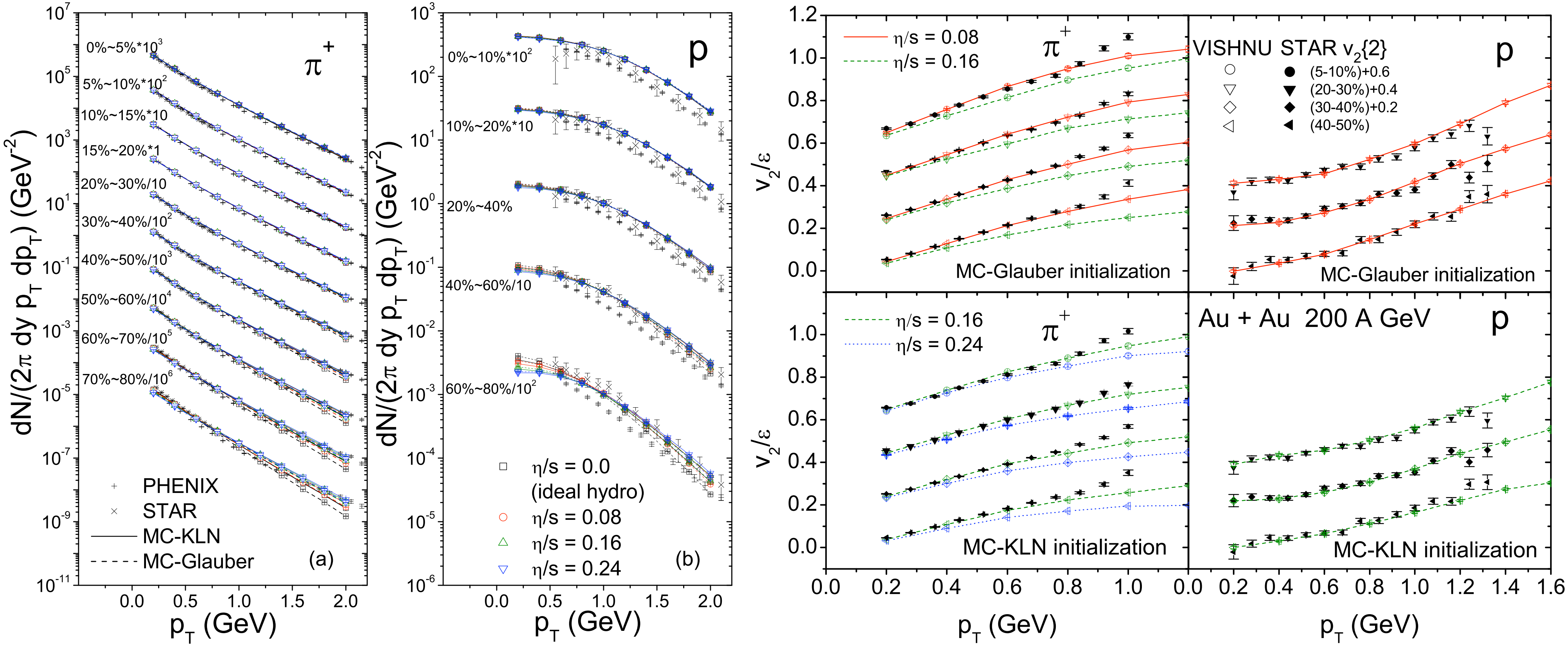
H. Song, S.A. Bass, U. Heinz, T. Hirano, C. Shen, PRL106 (2011) 192301



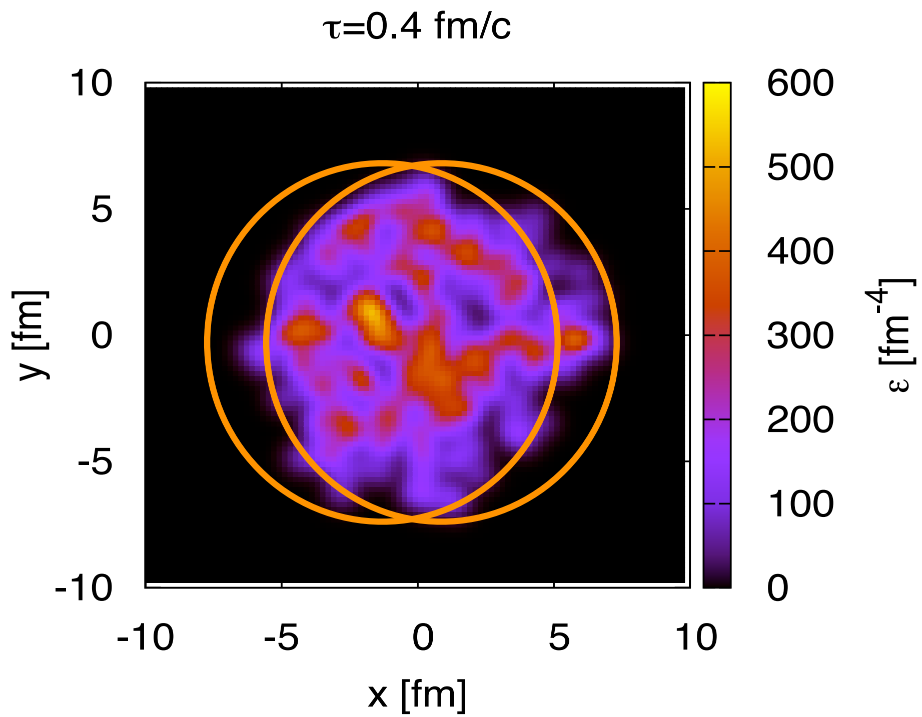
It works! (especially w. Hydro+cascade)

Basic $O(\ell_{\mathrm{mfp}}/L)$ come out right

VISHNU (Song, Bass, Heinz, Hirano, Shen, PRC 83 (2011) 054910)



Determining the Shear Viscosity of QGP with Correlations:



1. Characterize energy density with ellipse
   - Elliptic Shape gives elliptic flow

$$v_2 = \langle \cos 2\phi_{\mathbf{p}} \rangle$$

2. Around almond shape are *fluctuations*
   - Triangular Shape gives v_3 (Alver)

$$v_3 = \langle \cos 3(\phi_{\mathbf{p}} - \Psi_3) \rangle$$

3. Hot-spots give *correlated* higher harmonics
   - Systematized and simulated

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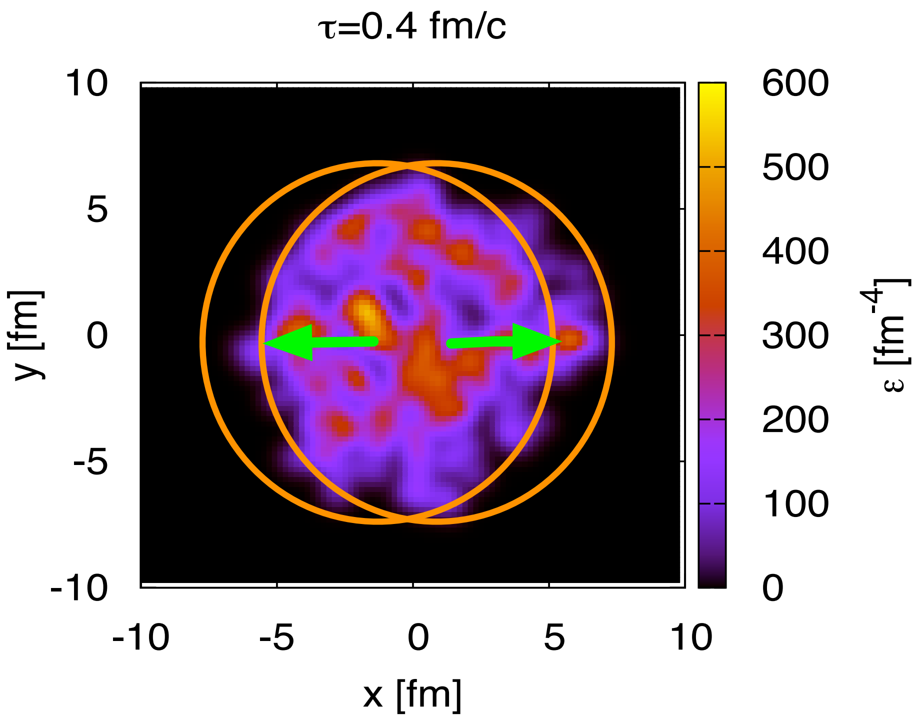

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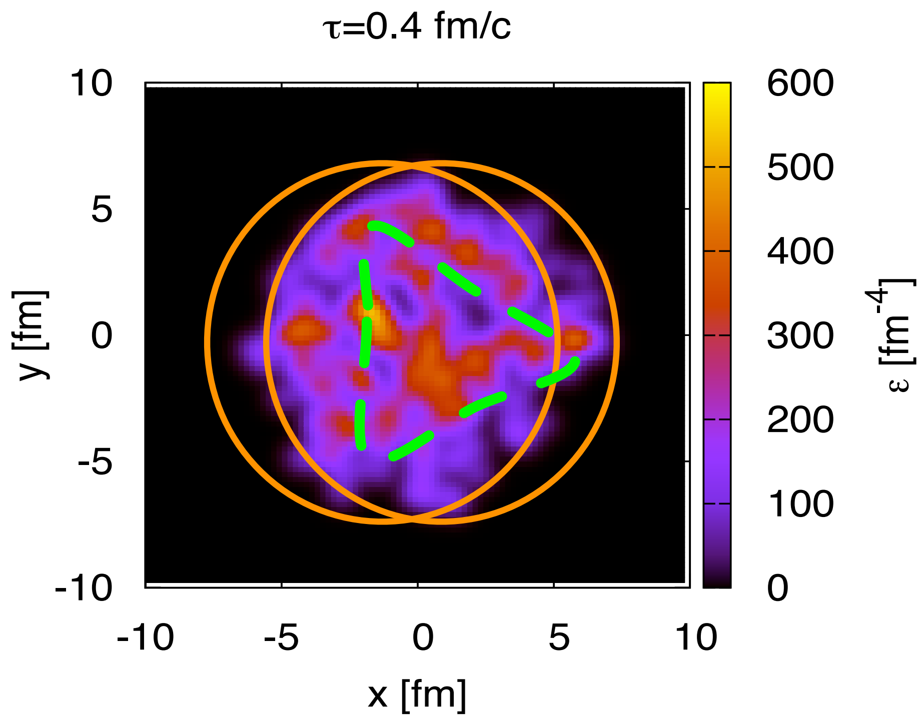

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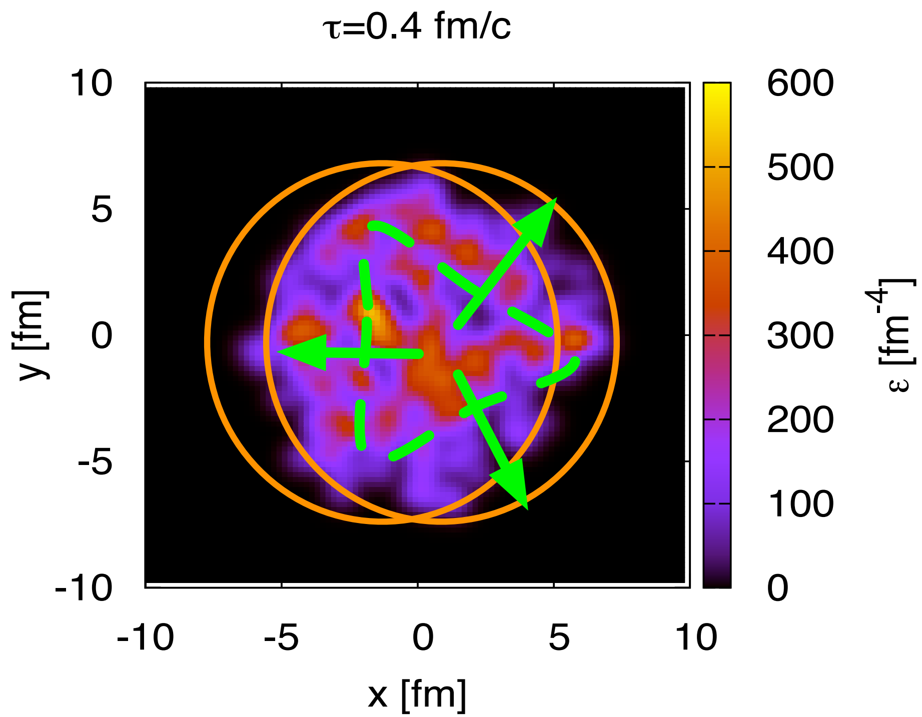

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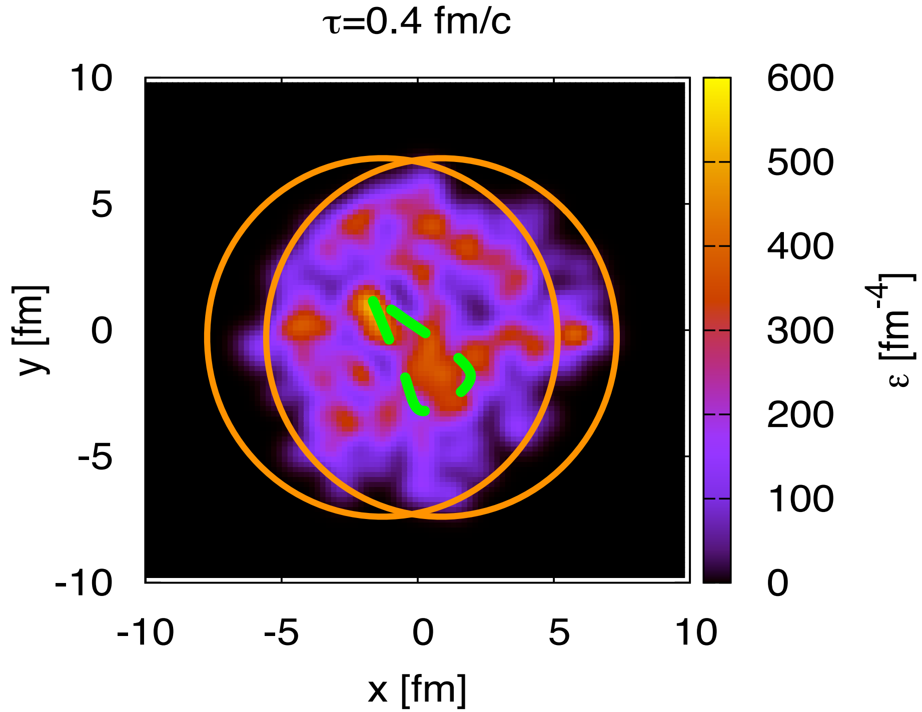

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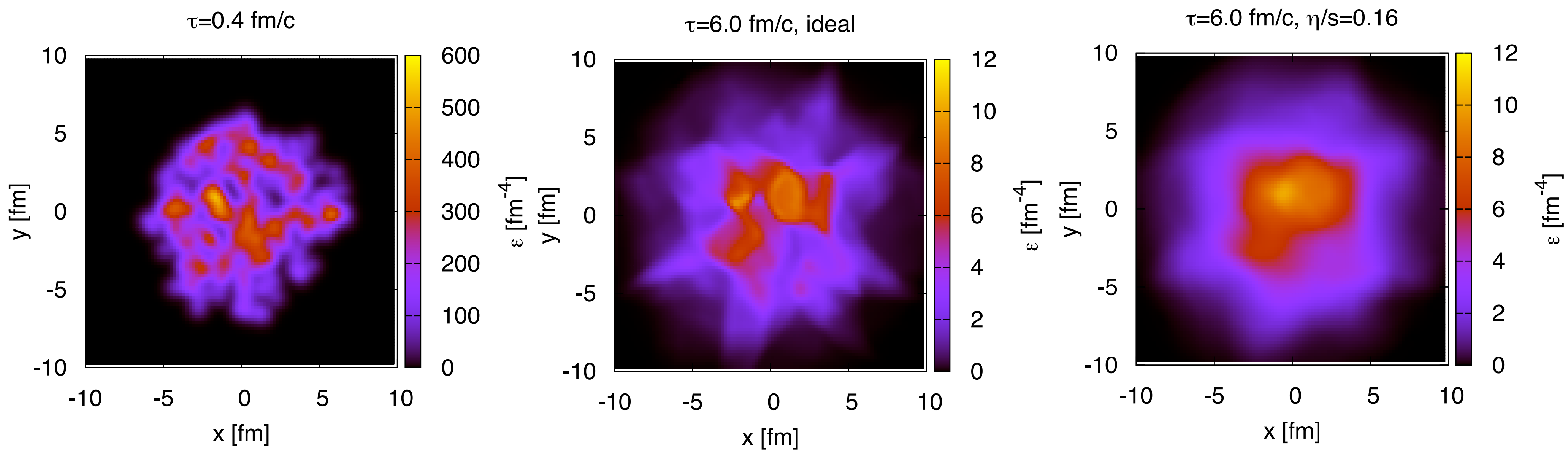
Why is this useful?

1. Different harmonics are damped differently by viscosity
2. Depends on system size, momentum, . . .

Experiments <u>vastly</u> over constrain hydrodynamic predictions for QGP!

3+1 E by E viscous hydro simulations by Schenke *et al*

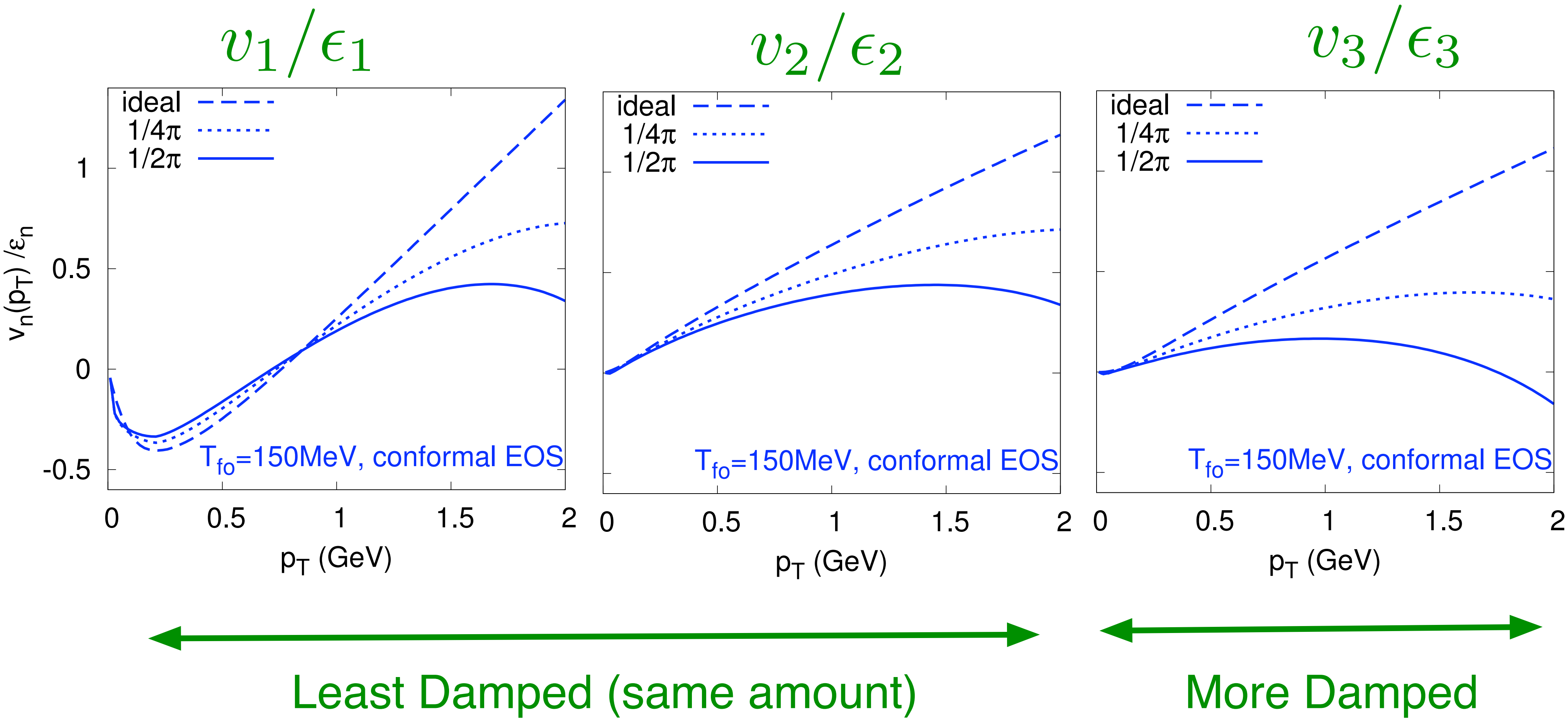
Initial   Final Ideal   Final Visc.



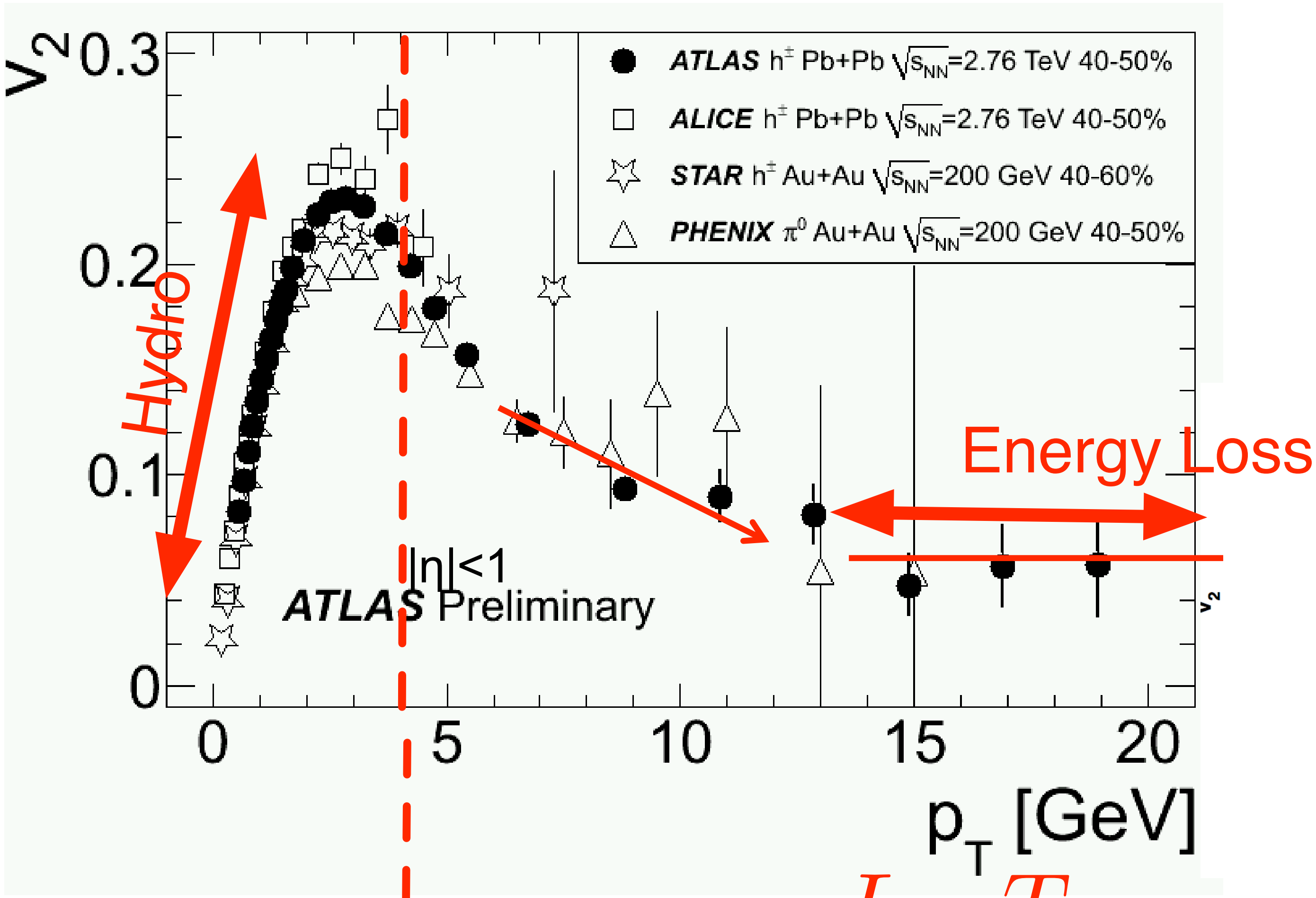
Higher harmonics are damped most by viscosity

Pattern to Viscous corrections

for example Yan Li & DT



General pattern for arbitrary cumulant worked out: A. Yarom, S. Gubser



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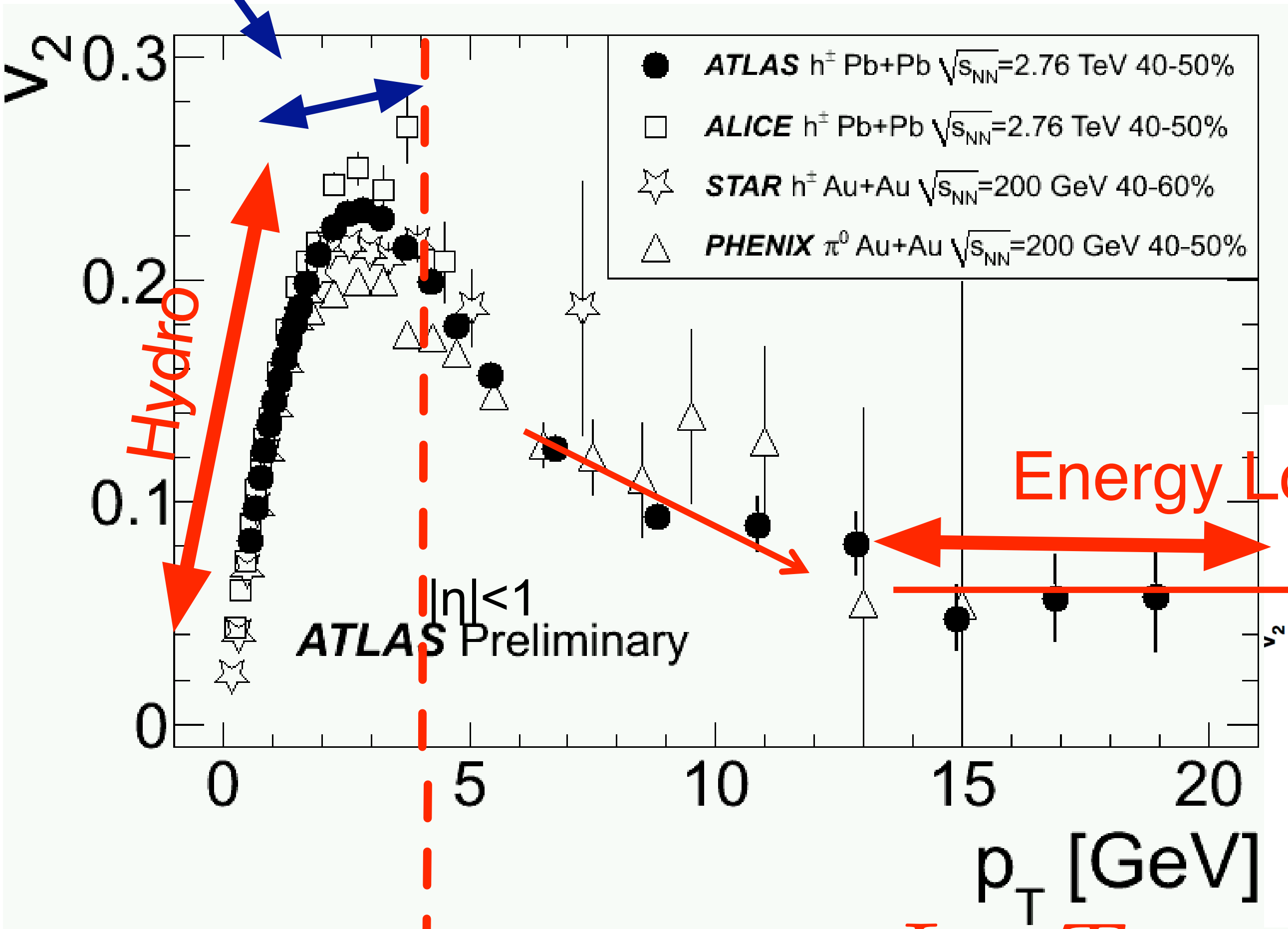
Higher pt but still hydro

$$(\ell_{\rm mfp}/L)\frac{p_T}{T} < 1$$



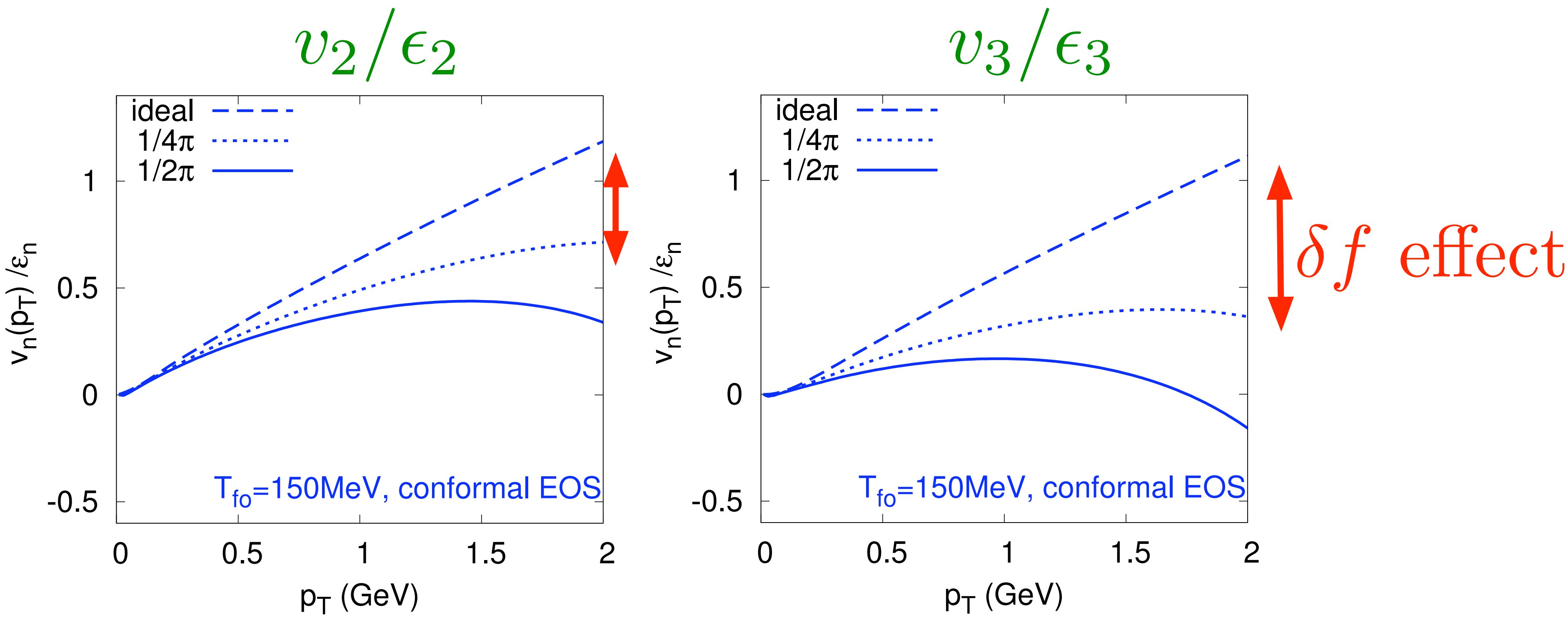
$$\frac{\ell_{\rm mfp}}{L} \to 0$$

$$\frac{L}{\ell_{\rm mfp}}\frac{T}{p_T} \to 0$$

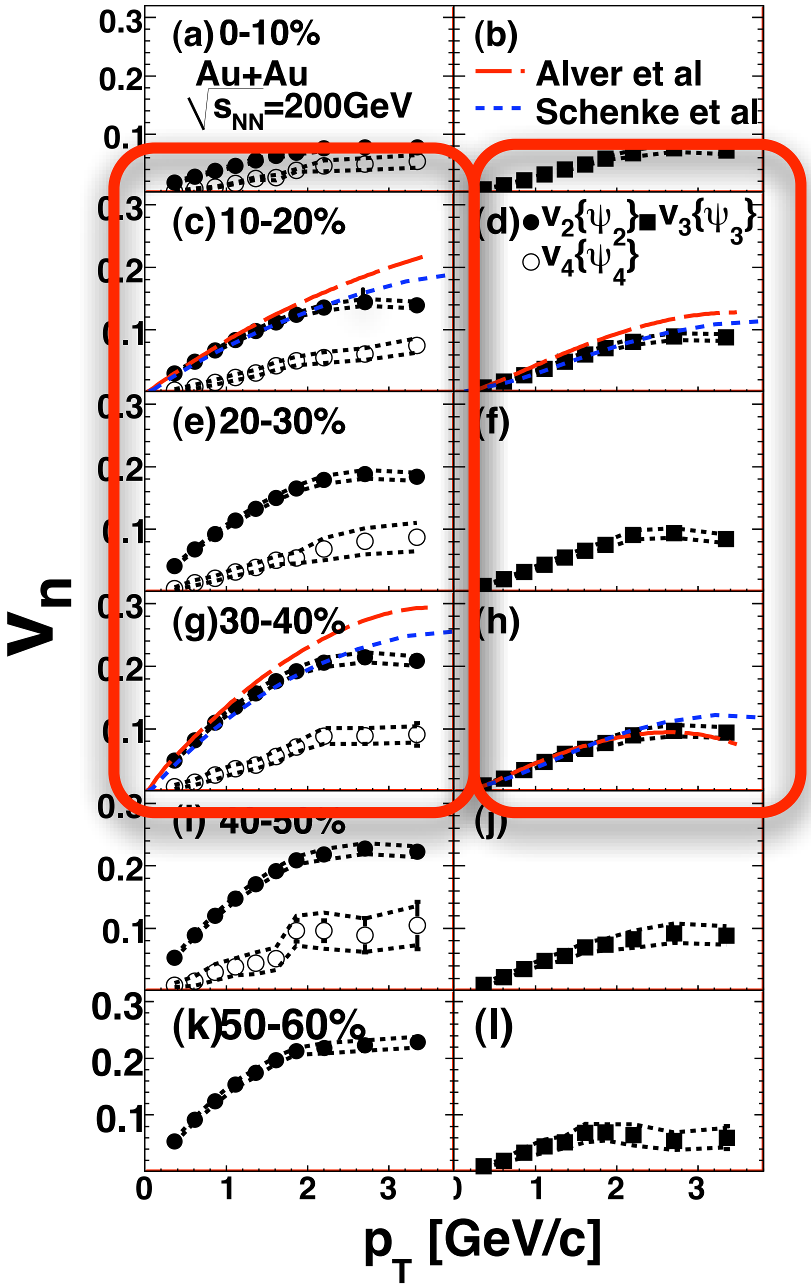
Viscous corrections grow with p_T and "n"

- δf related to energy loss at modest momenta

$$\underbrace{f(\mathbf{p})}_{\text{phase space dist}} = \underbrace{e^{-E_{\mathbf{p}}/T}}_{\text{Ideal (maxwell) distribution}} + \underbrace{\frac{p^i p^j}{2T\,\langle dp/dt\rangle_{\mathbf{p}}}\langle \partial_i u_j \rangle}_{\sim(\ell_{\rm mfp}/L)p_T/T}$$



Phenix v_3 data



Hydro Works:

(schenke, luzum)

1. Centrality dependence of v_2 and v_3

$$\sim (\ell_{\rm mfp}/L)$$

2. Relative strength of v_2 and v_3

3. p_T dependence of viscous corrections

$$\sim (\ell_{\rm mfp}/L)\frac{p_T}{T}$$

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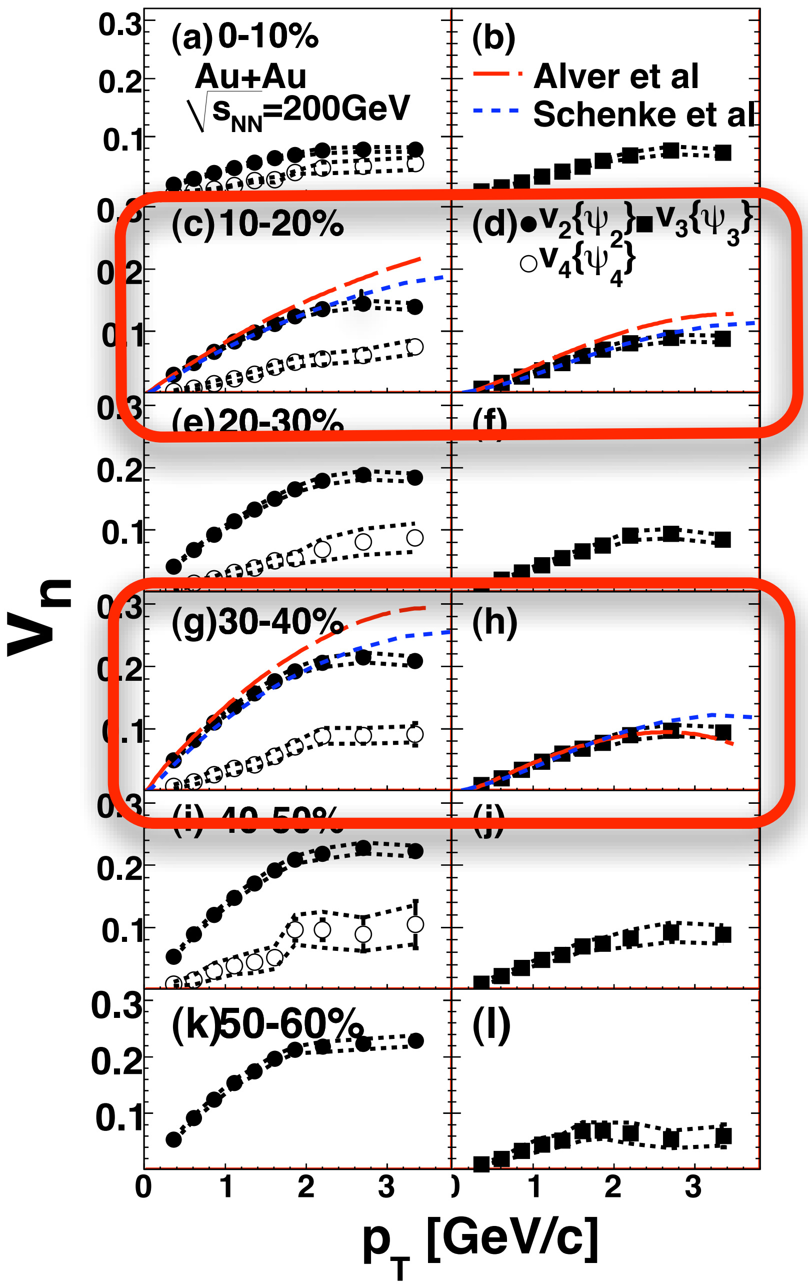

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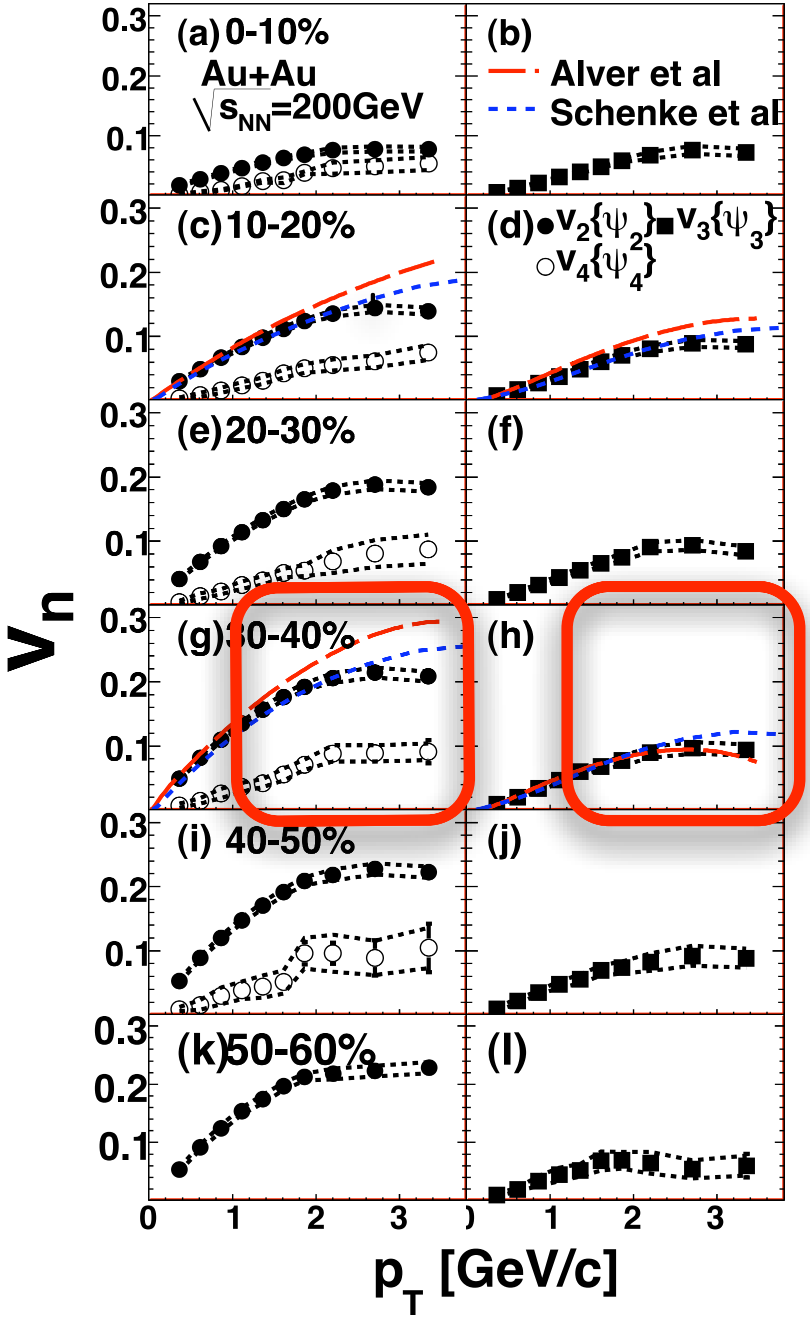

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Hydro

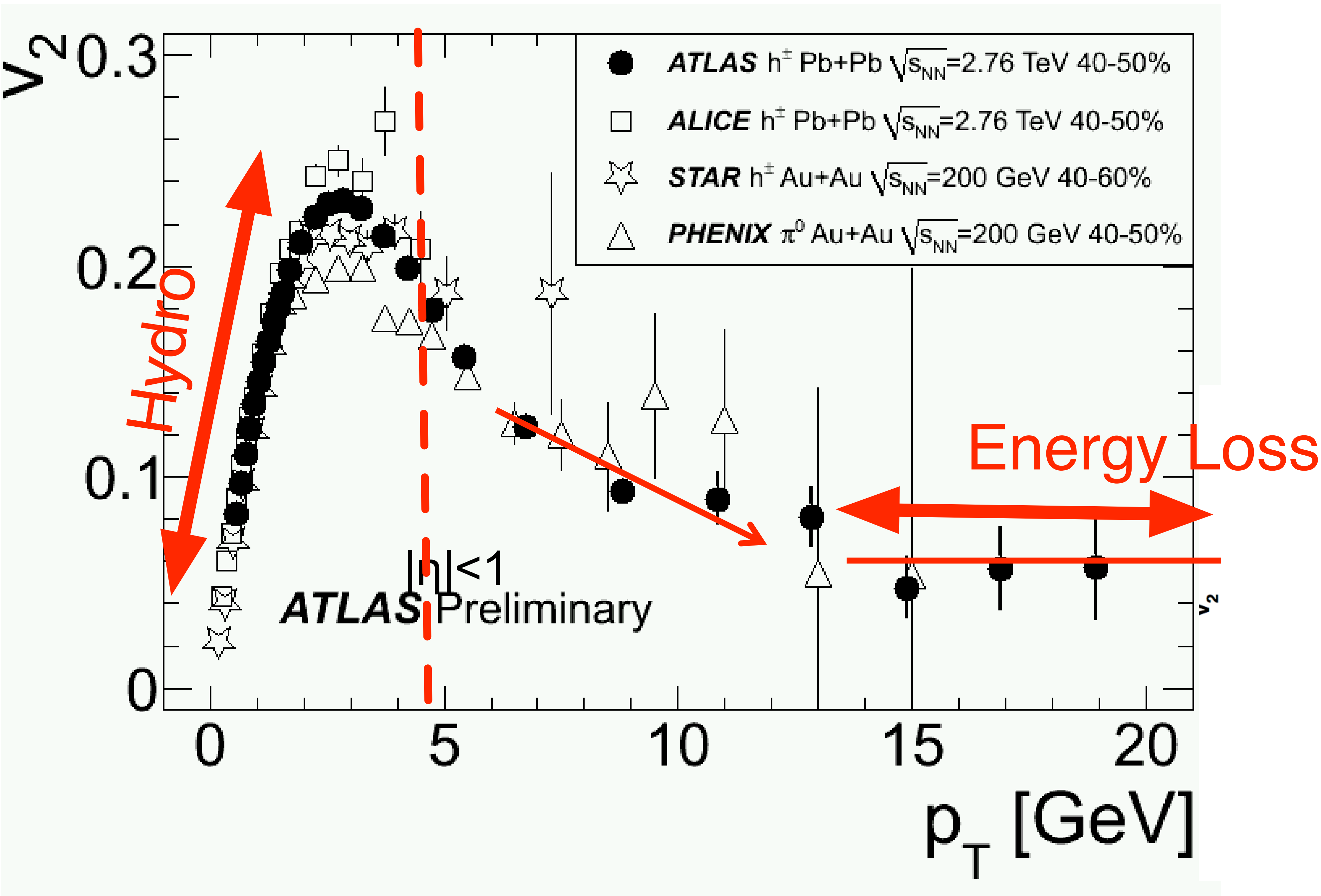
Why I believe that there's hydro at RHIC (and why you should too):

✓ Ideal hydro works kind-of (not for today)

✓ Viscous corrections <u>systematically</u> capture deviations of data from ideal hydro

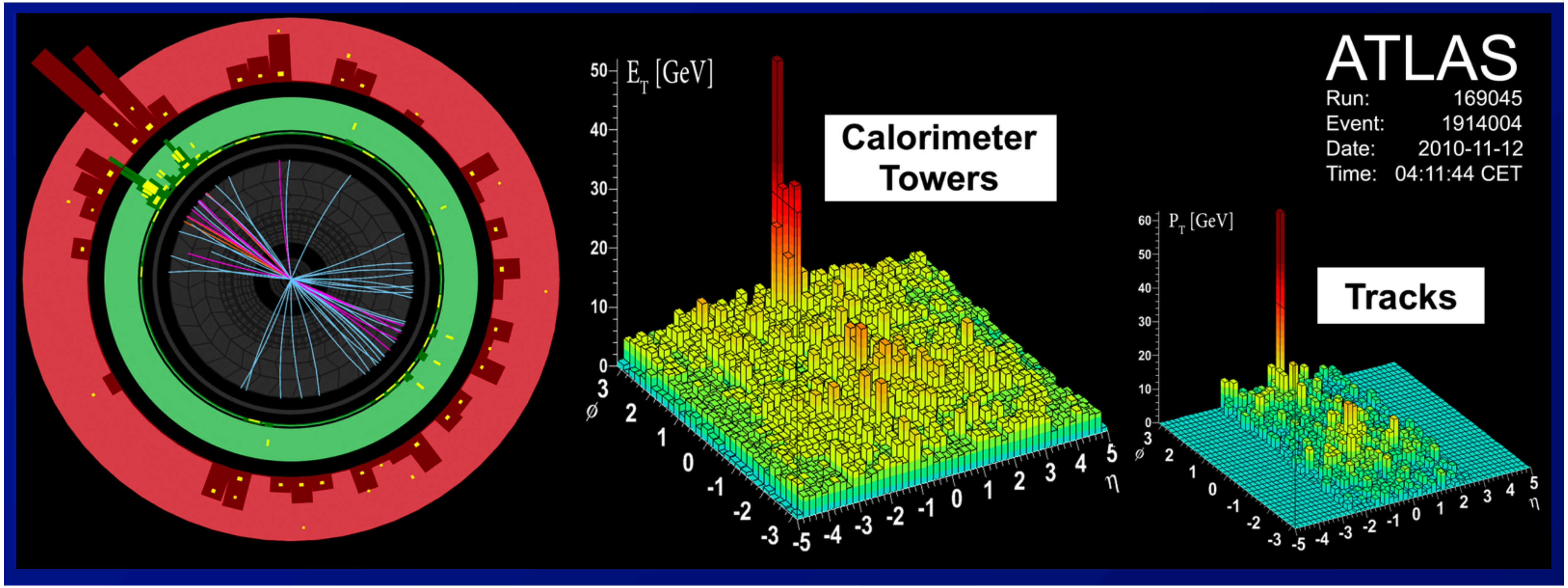
Makes the bounds $1/4\pi < \eta/s < 3/4\pi$ kind of convincing

Energy Loss



ATLAS h± Pb+Pb √sNN=2.76 TeV 40-50%
ALICE h± Pb+Pb √sNN=2.76 TeV 40-50%
STAR h± Au+Au √sNN=200 GeV 40-60%
PHENIX π0 Au+Au √sNN=200 GeV 40-50%
|η|<1
ATLAS Preliminary
Hydro
Energy Loss
v2
pT [GeV]

Dijet Asymmetries at the LHC



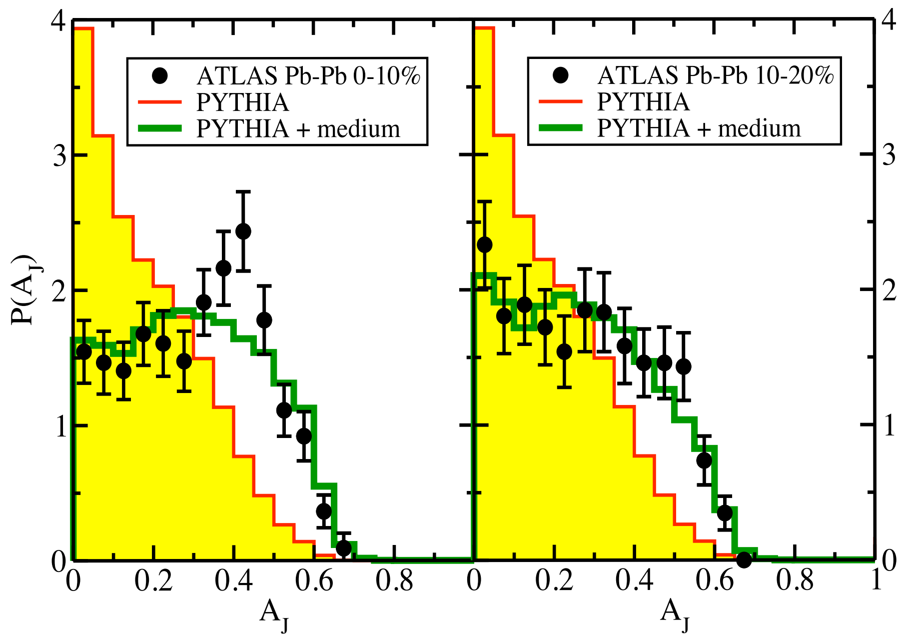
$$A_J \equiv \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

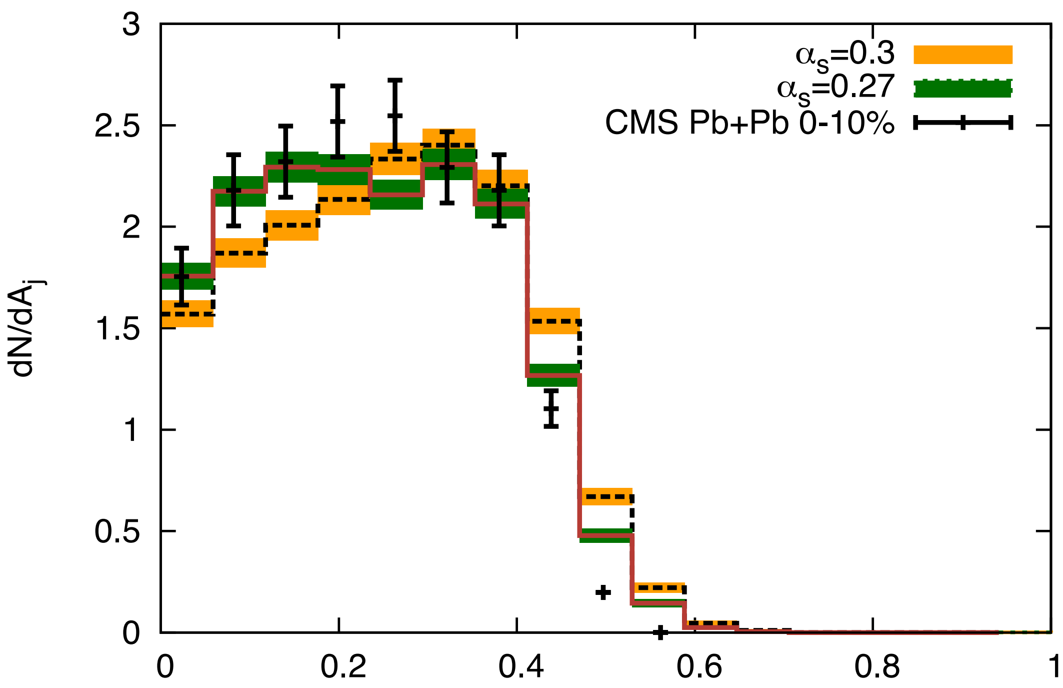
Theoretical Calculations seem to get the Dijet Asymmetry

Prediction:

Qin, Muller: arXiv:1012.580

Young, Schenke et al: arXiv:1103.5769

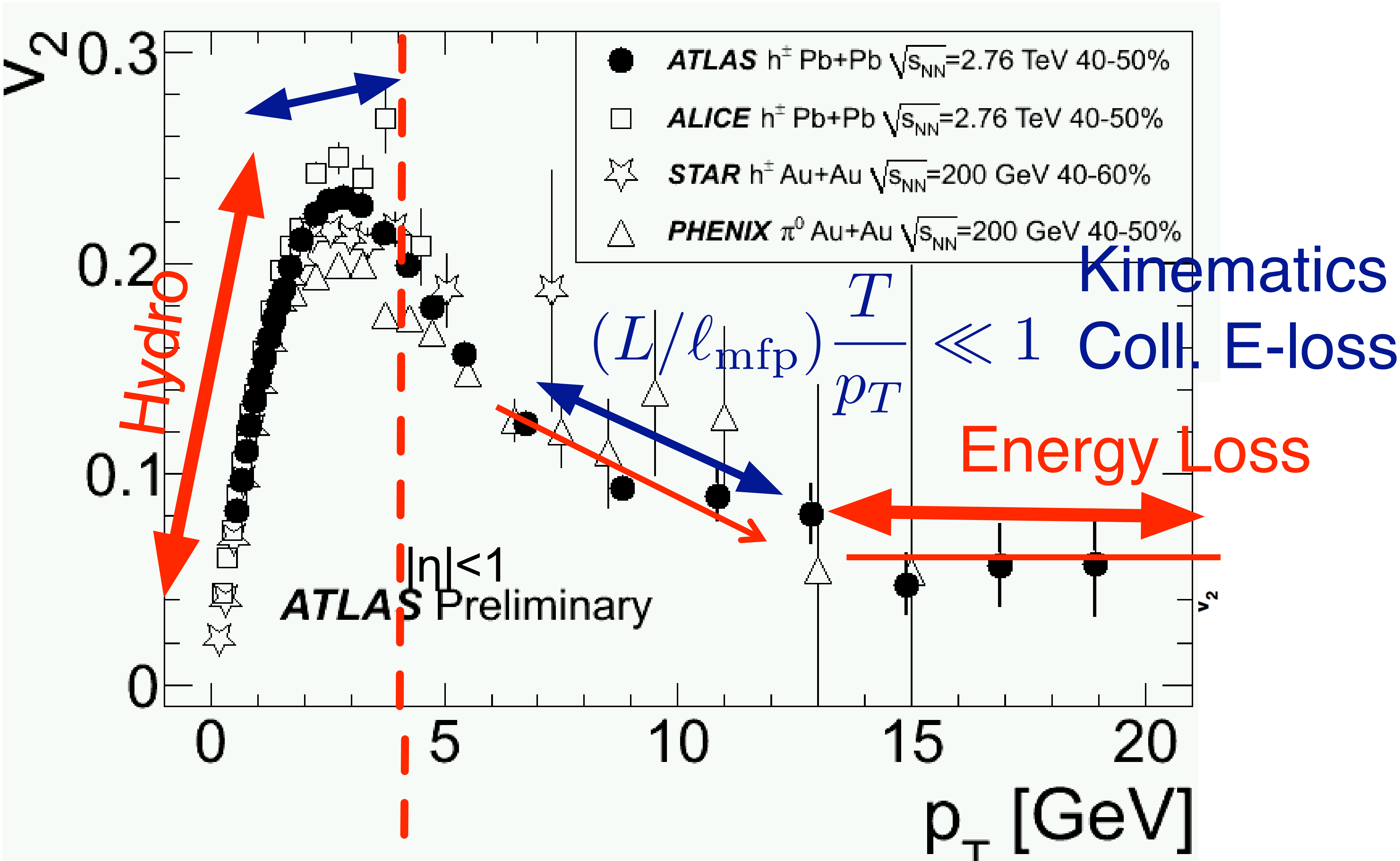




See also, J. Casalderrey-Solana et al arXiv:102.0745

All calculations move soft remnants away from the jet with “soft” $1/p_T$ transport mechanisms

(Are they consistent with measured j_T and longitudinal momentum distributions though?)

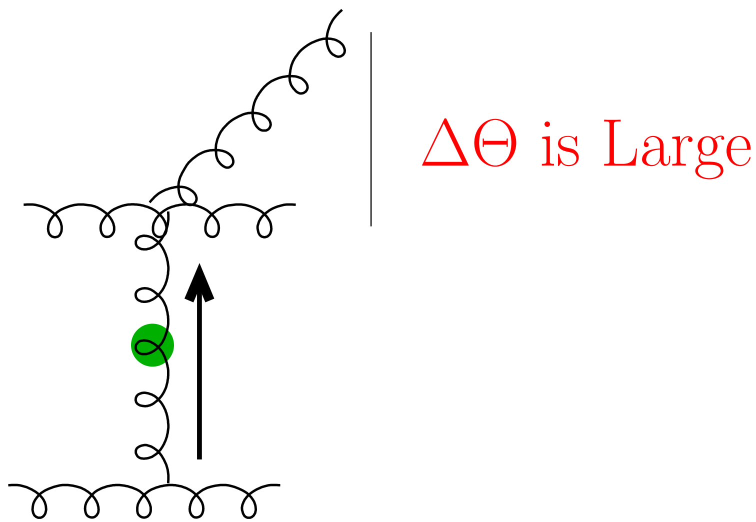


$$\frac{\ell_{\rm mfp}}{L} \to 0$$

$$\frac{L}{\ell_{\rm mfp}}\frac{T}{p_T} \to 0$$

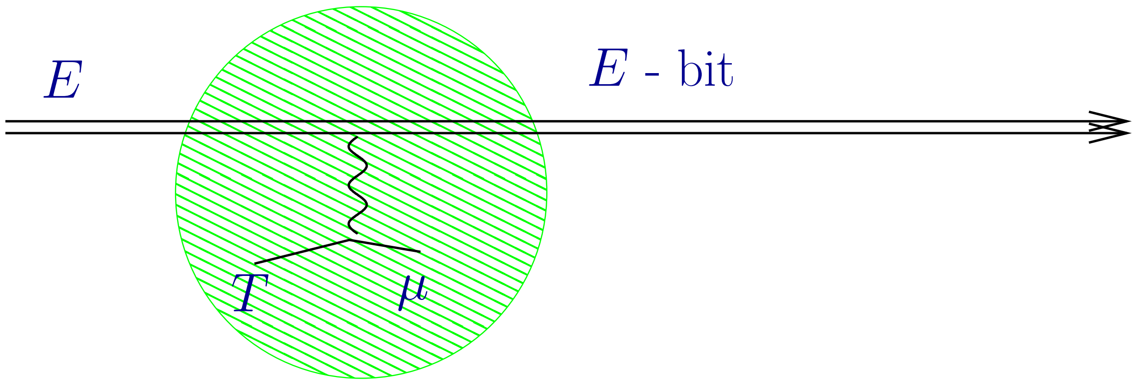
Energy loss at sub-asymptotic energies is important:

1. Kinematic constraints limit the agreement between energy loss formalisms
   - See the report of the Jet Collaboration: arXiv:1106.1106
2. Finite energy leads to large angle emission outside of radiative loss formalism



Radiative and Collisional Loss:

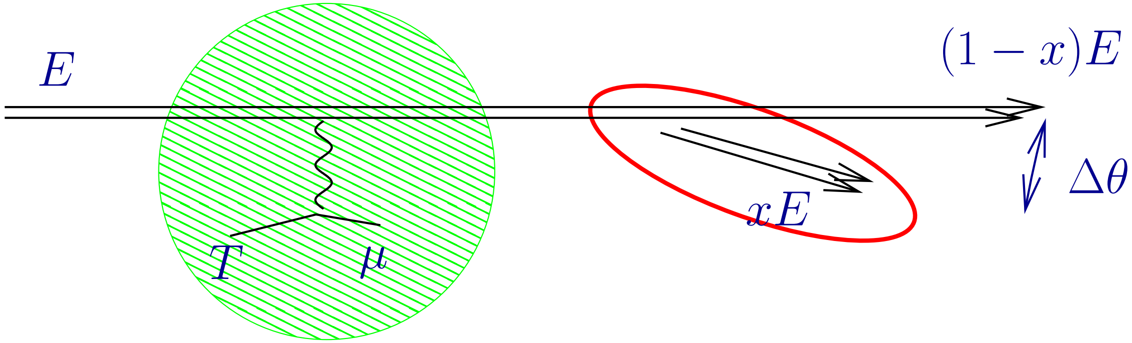
Collisional Energy Loss: $\frac{dp^{LO}_{\rm coll}}{dt}(\mu)$



Features:

1. Plasma is excited: $T \ll \mu \ll E$
2. Hard particle in hard particle out

Radiative Loss: $\frac{dp_{\rm rad}}{dt}(\mu)$



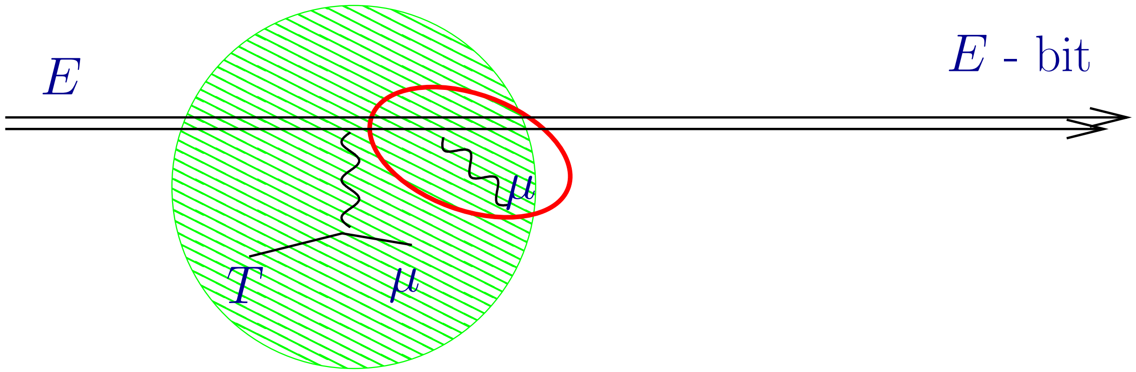
Features:

1. Plasma is excited: $T \ll \mu \ll E$
2. Hard particle in, two hard part. out
   - We require $xE \gg \mu$

As the bremmed energy gets lower and lower, the angle $\Delta\theta$ gets larger and larger

Radiative and Collisional Loss

Soft Radiative Loss: $\frac{dp_{\text{coll}}^{NLO}}{dt}(\mu)$

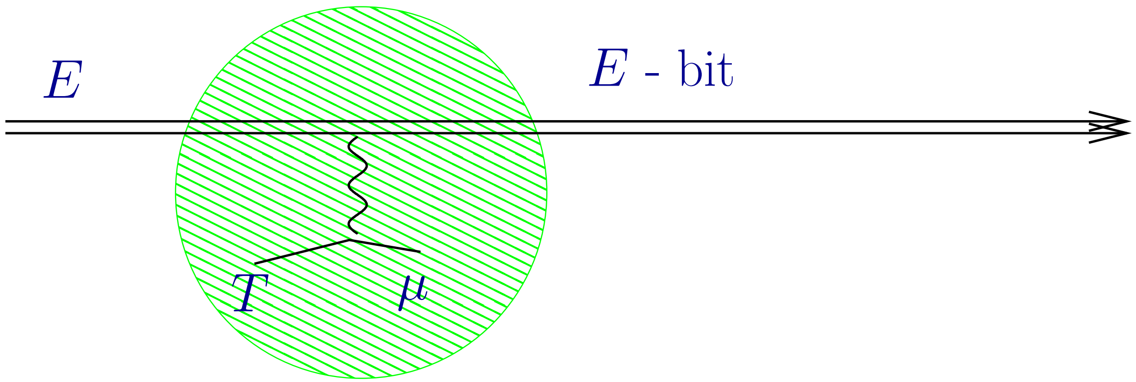


Features:

1. Plasma is excited: $T \ll \mu \ll E$
2. Hard particle in, one hard particle out

This is higher order correction to the collisional E-loss rate

Collisional Energy Loss: $\frac{dp_{\text{coll}}^{LO}}{dt}(\mu)$

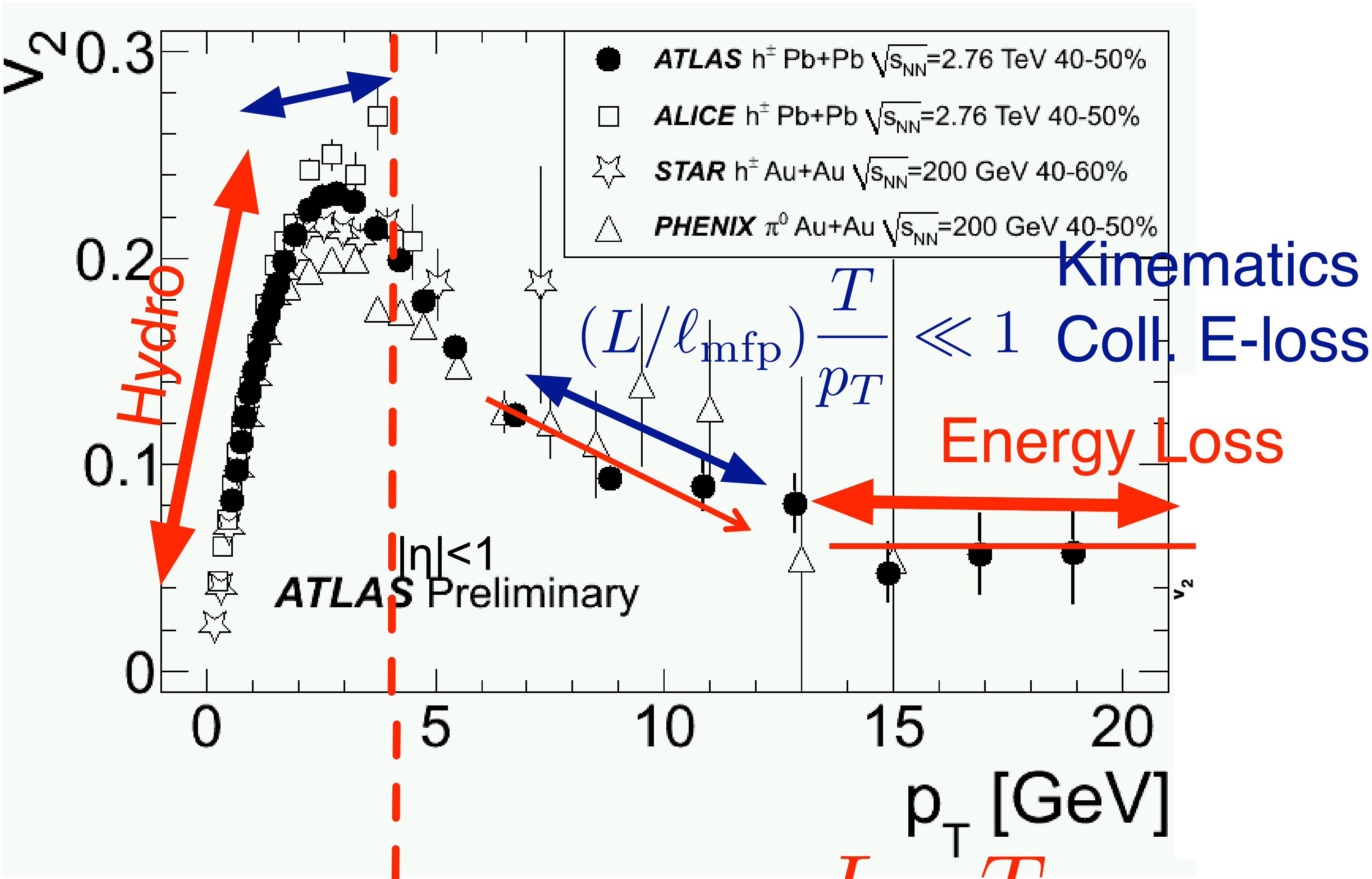


Final result is independent of μ: $$\underbrace{\frac{dp_{\text{coll}}^{LO}}{dt} + \frac{dp_{\text{coll}}^{NLO}}{dt}}_{\text{Phenomenological Coll E-loss}} + \underbrace{\frac{dp_{\text{rad}}}{dt}}_{\text{Radiative Loss}}$$

Summary

Higher pt but still hydro

$$(\ell_{\rm mfp}/L)\frac{p_T}{T} < 1$$



$$\frac{\ell_{\rm mfp}}{L} \to 0$$

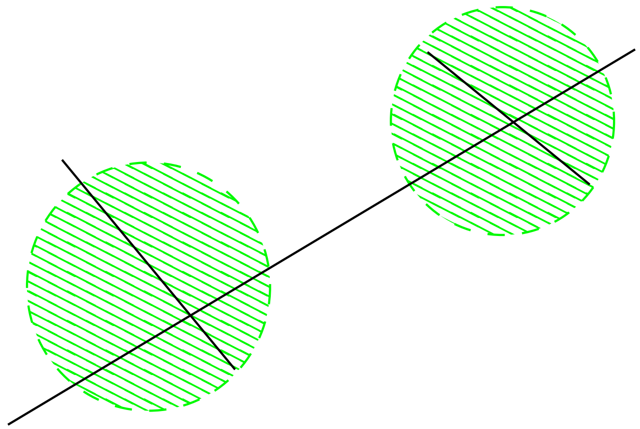
$$\frac{L}{\ell_{\rm mfp}}\frac{T}{p_T} \to 0$$

Summary

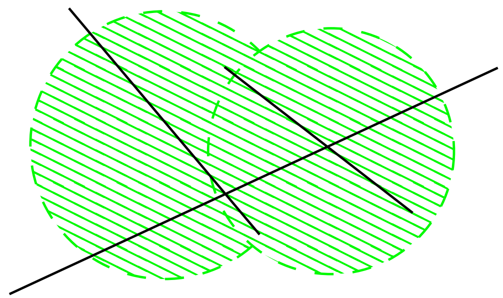
1. Hydro works amazingly well
2. Energy loss is progressing
3. What got left out (maybe):
    - Is a quasi particle picture valid? At what temperature ?
        - See quark matter talks: Nan Su, Olaf Kaczmarek

Quasi Particles are not?

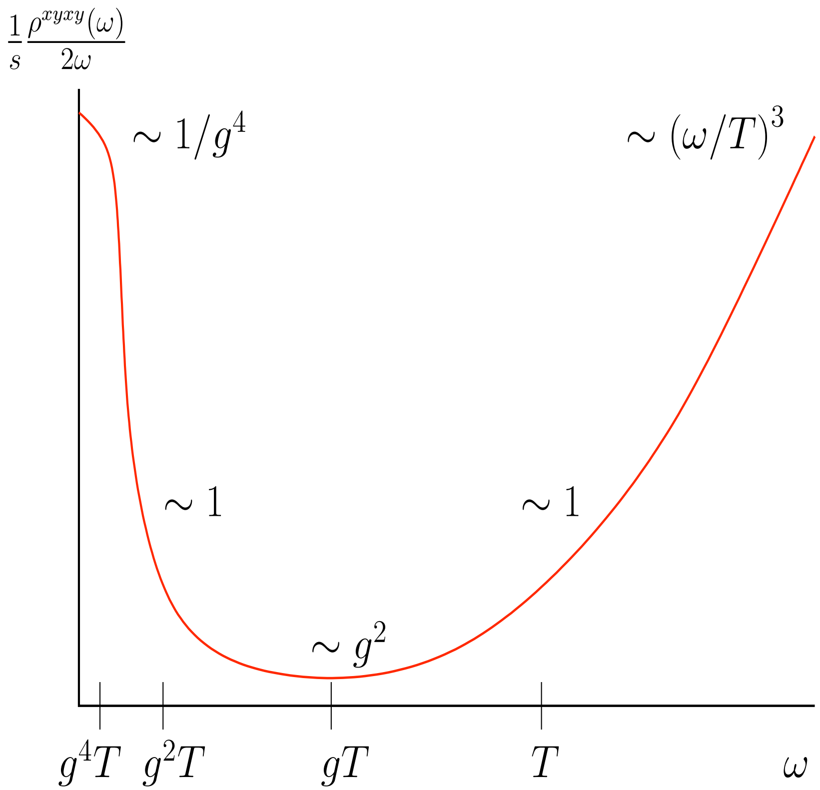
Quasi particle pciture: Independent scatterings

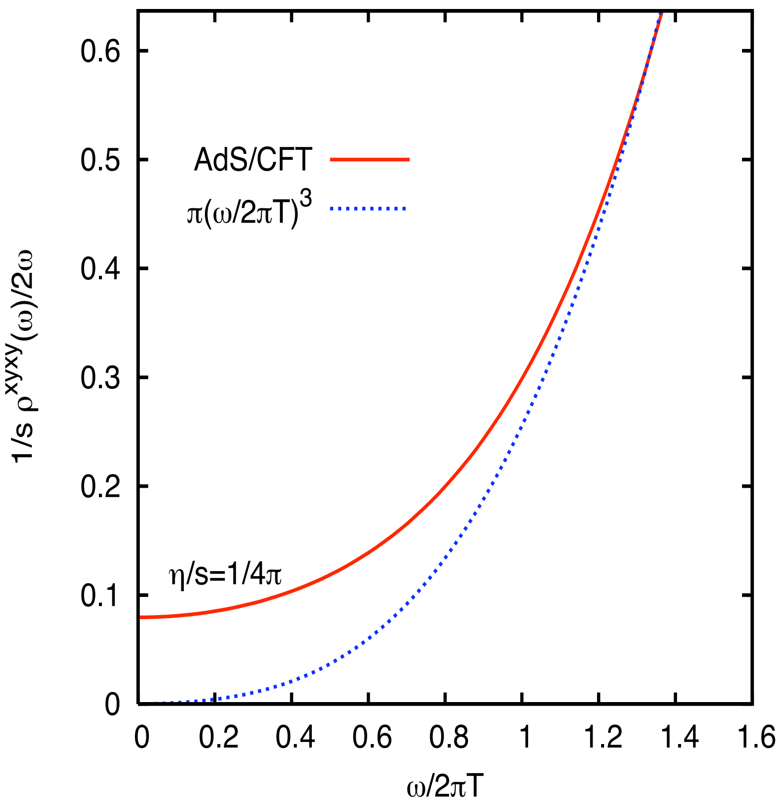


No quasi−particles



Makes Predictions for spectral densities:

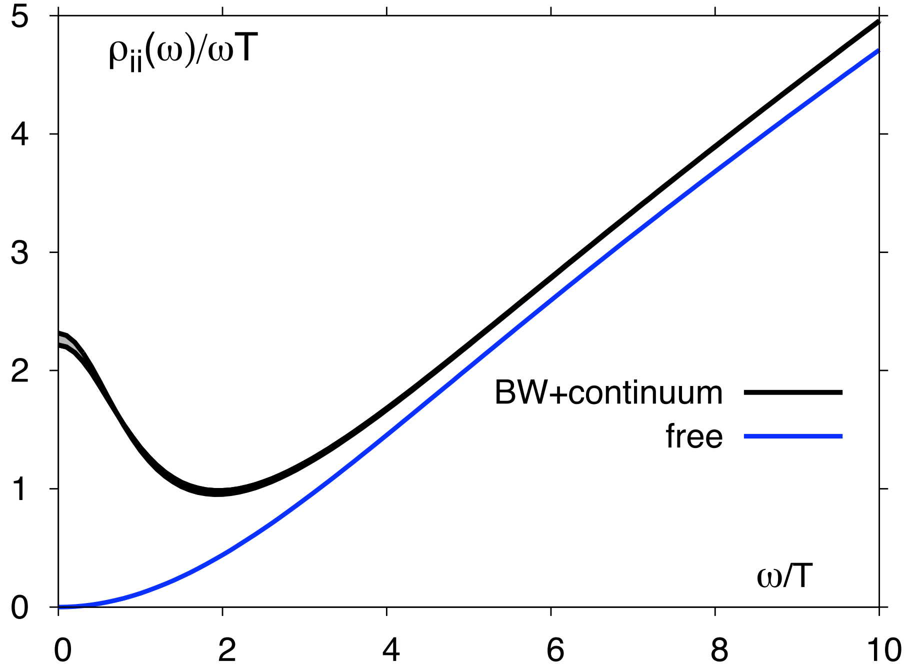




Quasi particle picture from Lattice spectral Densities (Olaf Kaczmarek, Quark Matter)

- Fits to Lattice Euclidean Data

Best Fit



Range of fits